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Strained $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ window layers for indium phosphide solar cells

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The efficiency of indium phosphide solar cells might be improved by a wide-band-gap window layer. In this work we calculate the performance of InP solar cells with a strained (pseudomorphic) $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ window layer. Calculations show that the efficiencies of baseline and optimized p^+n cells are increased to more than 22% and 24% (AM0, 25 °C), respectively, for $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ window layer of 10 nm thickness. Comparatively little improvement is found for n^+p cells.

Indium phosphide (InP) solar cells show extremely low radiation-induced degradation compared to currently used gallium arsenide (GaAs) and silicon (Si) cells.¹ The conversion efficiency of InP cells, however, is significantly lower than that achieved by GaAs cells. If efficiency comparable to GaAs could be achieved, InP solar cells would be an extremely useful power source for satellites and space missions requiring long lifetimes with little degradation. A new design of the InP cell with high performance could thus have a significant impact on the lifetime of power systems for satellites with orbits that pass through the Van Allen radiation belts, such as the Earth Observation System (EOS) satellites² and low-orbit communications satellites such as "Iridium," that are now under development. Efficiencies achieved to date are limited by high values of surface recombination velocity ($\text{SRV} \sim 10^7$ cm/s).^{3,4} n -on- p cells are less affected by the SRV than p -on- n cells,^{4,5} because n -on- p cells have relatively thin emitters (~ 0.02 μm).

To date, most cell development work has been focused on n -on- p type structures.⁶ A recent modeling study⁷ suggests p^+n structures would become more efficient than n^+p structures if surface recombination is reduced. For structures grown by heteroepitaxy, the p -on- n structure also avoids the problem of n -type impurity doping into the base from Si or Ge substrates.

Surface recombination velocity can be reduced by use of a wide-band-gap window layer on the surface. Use of wide-band-gap window layers on GaAs⁸ and Si⁹ solar cells has resulted in significant improvements in performance. Unlike the case of GaAs, where $\text{Al}_x\text{Ga}_{1-x}\text{As}$ forms a naturally lattice-matched ternary system for all values of x , lattice-matched heteroepitaxial systems for InP are relatively limited. The ternary compound $\text{In}_x\text{Al}_{1-x}\text{As}$ is a candidate window layer for InP solar cells, but at the lattice-matched composition of $x=0.52$, the band gap is only slightly higher than that of InP. The steep slope of the band gap with change in lattice parameter for InAlAs suggests that a significant increase in window layer transparency could be achieved by only a small deviation of the lattice parameter from the lattice-matched value of 5.86 Å.

$\text{In}_x\text{Al}_{1-x}\text{As}$ has been widely used in electronic and optical devices. Most of the work has been focused on $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$, which is lattice matched to InP. This resulted in the state of the art performance for several types of opto-

electronic devices.¹⁰ Use of lattice-matched $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ as a window layer for InP solar cells was analyzed in Ref. 11. This work shows that while efficiency is improved, the achievable efficiency is limited by absorption in the InAlAs layer, due to the small difference in E_g for lattice-matched material. If the constraint of lattice matching can be removed by use of strained (pseudomorphic) material, a further increase in performance could be realized.

The optimum choice will be to use an InAlAs layer with a band gap as wide as possible to reduce the light absorption losses. However, wider band-gap compositions have higher lattice mismatch and hence a lower critical thickness. We have selected a composition of $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ for our calculations. At this composition the lattice mismatch with InP is -0.77% and the band-gap energy is around 1.8 eV. This wide band gap makes the $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ layer nearly transparent to the incoming light useful for the InP solar cell. For a lattice-mismatch of -0.77% , calculations using the Matthews and Blakeslee (M-B)¹² theory gives an estimation of about 13 nm for the critical layer thickness. More recent work by Bennett and del Alamo¹³ shows that the actual critical layer thickness is considerably larger. HFETs with 30 nm of strained $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ layer showed no degradation due to mismatch [see Fig. 10(b) of Ref. 13]. Using high-resolution x-ray diffraction, it was found that for a lattice mismatch of $\leq \pm 1\%$, the crystalline quality of the InAlAs epitaxial layer remains high to thicknesses up to 3–9 times the M-B critical layer thickness.¹³

In the calculations reported in this letter, we have considered the 10 nm thick $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ strained layer as a window, which is less than the critical layer thickness calculated by the most conservative (M-B) approximation.

Little or no information is available on the optical, electrical, and other properties of ternary InAlAs. We have attempted to estimate the critical parameters based on the literature information available on InP and lattice matches $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$. The band-gap energy of the strained $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ is 1.8 eV. The strained layer lattice constant is 5.815 Å, compared to 5.86 Å for InP. A value of 0.294 eV for the conduction band energy discontinuity, the same as for lattice matched InAlAs, is assumed. The intrinsic carrier concentration, n_i for the strained $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ was scaled from the value for InP (8×10^6 cm⁻³ Ref. 14) using the relation:

$$n_i(\text{In}_{0.40}\text{Al}_{0.60}\text{As}) = n_i(\text{InP}) \exp[-\Delta E_g / (2kT)], \quad (1)$$

where ΔE_g is the band-gap difference, k is the Boltzmann's

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TABLE I. Baseline and optimized p^+n InP solar cell parameters used in the calculations.

	Baseline	Optimized
Grid shadowing, %	5	5
Series resistance, $\Omega \text{ cm}^2$	0.3	0.3
Two layer antireflection coating (ZnS/MgF ₂), nm	50, 100	50, 100
Emitter		
Thickness, μm	0.15	0.15
Doping, cm^{-3}	10^{18}	10^{18}
Front surface recombination velocity, cm/s	10^7	10^7
Minority carrier diffusion length, μm	0.5	2
Base		
Thickness, μm	5	5
Doping, cm^{-3}	10^{17}	10^{17}
Back surface recombination velocity, cm/s	10^7	10^7
Minority carrier diffusion length, μm	2	5

constant, and T is the temperature in K. The optical absorption coefficient of the strained InAlAs was assumed to be the same as InP but shifted in wavelength by the band-gap ratio (1.35/1.8). Other parameters were assumed to be the same as of InP in the calculations.

In this work we have considered two designs of the InP cells. The baseline cell design uses materials parameters representative of the current state-of-art in InP solar cells. The optimized cell design assumes improvements in materials parameters which we believe are achievable by suitable processing improvements. More details about InP cell modeling are available elsewhere.^{4,5,7} Table I describes the design parameters of p^+n InP cells used in the calculations reported here. The PC-1D numerical code¹⁵ was used to calculate the cell current-voltage characteristics and the external quantum efficiency response with and without the InAlAs window. A strained $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ window layer with surface recombination velocity of 10^7 cm/s was assumed. The window layer doping and diffusion length have been assumed equal to the cell emitter values (see Table I). To avoid heavy doping effects, moderate doping (10^{18} cm^{-3}) of the window and emitter regions have been considered. An optimum base doping of 10^{17} cm^{-3} was assumed.^{5,7}

Figure 1 shows the calculated I - V characteristics (AM0, 25 °C) of the baseline and optimized cell using the parameters of Table I. This figure also includes the calculated I - V results of the cell with the strained $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ window layer of 10 nm thickness. The use of the window on the baseline cell improves its efficiency from 14.7% AM0 to slightly over 22%, while the optimized cell efficiency increases from 15.4% AM0 to, in excess of, 24%. The greater improvement of the optimized cell is due to its reduced bulk recombination. For comparison we have calculated the I - V curve of a p^+n InP cell with decreased front SRV. A reduction in the front SRV by three orders of magnitude, from 10^7 to 10^4 cm/s, is necessary to achieve the efficiencies obtained with the 10 nm window layer. This demonstrates that the window layer is effectively improving the SRV.

Calculations were also performed to study the effect of a strained window layer on the efficiency of n^+p InP solar cells. Comparatively little improvement ($\sim 1\%$) in efficiency

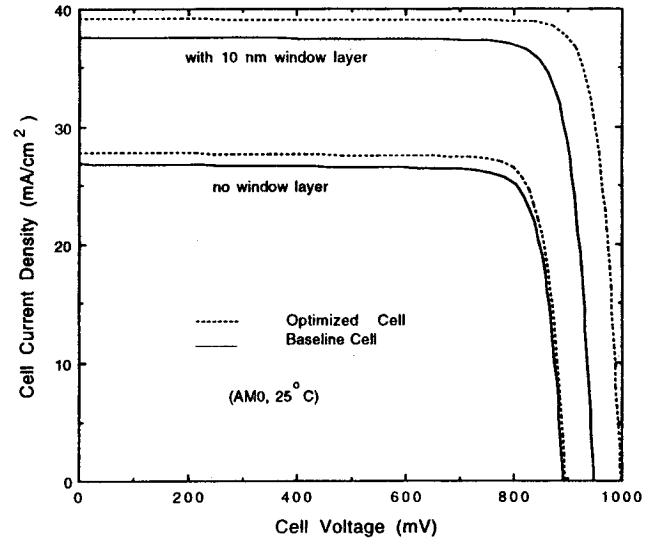


FIG. 1. Calculated current-voltage characteristics (AM0, 25 °C) of the baseline and the optimized p^+n InP cell without and with 10 nm $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ window layer design.

was obtained for these cells. These results can be explained by the large conduction-band energy discontinuity at the window/cell emitter (InAlAs/InP) interface. This discontinuity acts as an effective potential barrier for the minority carriers (electrons) of the p^+n cell, thereby stopping them from recombining at the surface. The holes in the n^+p cell emitter are not influenced much by the conduction band energy discontinuity, resulting in a less significant reduction in surface recombination.

As discussed earlier, $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ layers up to 30 nm thick can be grown with high crystalline quality, and HFETs (majority carrier devices) have been fabricated without any degradation due to mismatch.¹³ We have also calculated the

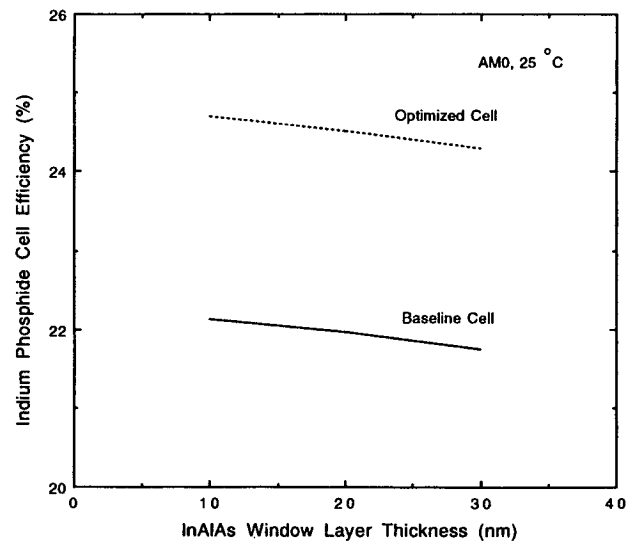


FIG. 2. Calculated p^+n InP AM0 cell efficiency as a function of strained $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ window layer thickness.

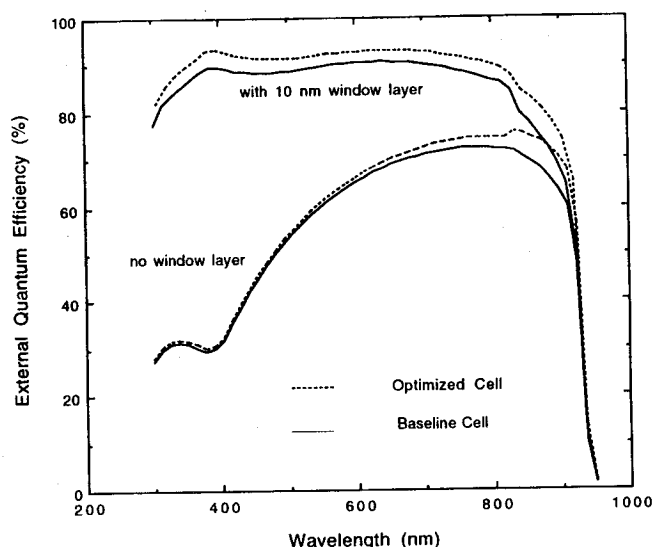


FIG. 3. Calculated external quantum efficiency response of the baseline and the optimized p^+n InP cell without and with 10 nm $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ window layer design.

p^+n cell efficiency for a 30 nm thick $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ window layer. The short circuit current is slightly reduced, but the efficiency remains high, as shown in Fig. 2. This slight reduction suggests that the wide-band-gap (1.8 eV) strained window layer is quite transparent to the incoming light, and absorption losses are negligible. However, it is desirable to keep the window layer thickness lower than the 30 nm, approximately the maximum allowable before the strained layers transition to unstrained layers by generation of misfit dislocations.

Figure 3 shows the calculated external quantum efficiency response for the baseline and the optimized p^+n InP solar cells in the 300–950 nm wavelength range. The cell response has been calculated without and with a 10 nm $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ window layer. From these results it is clear that the cell external quantum efficiency improves significantly with the lattice-mismatched window layer, especially the blue response. The cell external quantum efficiency curve with the 10 nm window is almost flat in the 375–800 nm wavelength range.

In conclusion, calculated results demonstrate that a wide-band-gap strained InAlAs layer is a potential candidate as a window layer material. Pseudomorphic InAlAs less than the critical layer thickness are required. The light absorption losses in the strained InAlAs considered are almost negli-

gible. A 10 nm strained $\text{In}_{0.40}\text{Al}_{0.60}\text{As}$ window layer results in significant improvement in cell efficiency and external quantum efficiency of p^+n InP cells. Comparatively little improvement has been predicted for the n^+p cells.

These calculations are based on extrapolated values of the optical and electrical parameters of InAlAs using the best available data. In particular, the results are sensitive to the absorption coefficient and to the conduction band discontinuity, neither of which has been measured for strained InAlAs. It must be cautioned that better measurements of the basic parameters are necessary to confirm these calculations, and may cause the predicted efficiencies to be different than expected.

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